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Note

Can plastics affect near surface layer ocean processes and climate?

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ABSTRACT

Plastics in the ocean are of great concern nowadays, and are often referred to as the apocalyptic twin of climate change in terms of public fear and the problems they pose to the aquatic and terrestrial environment. The number of studies focusing on the ecological effects and toxicity of plastics has substantially increased in the last few years. Considering the current trends in the anthropogenic activities, the amount of plastics entering the world oceans is increasing exponentially, but the oceans have a low assimilative capacity for plastics and the near-surface layer of it is a finite space. If loading of the oceans with plastics continues at the current rate, the thin sea surface microlayer can have a substantial amount of plastics comparable to the distribution of phytoplankton, at least in the major oceanic gyres and coastal waters in the future. Also, processes like biofouling can cluster microplastics in dense fields in the near-surface layer. Plastics can contribute to the warming or cooling of the water column by scattering and attenuating incoming solar radiation, leading to a potential change in the optical and other physico-chemical properties of the water column. We propose a new notion that changes in solar radiation in the water column due to the plastics have the potential to affect the physical processes in the ocean surface and near-surface layers, and can induce climate feedback cycles. The future can be very different, if plastics evolve as one of the key players affecting the ocean physical processes and hence this is the time to tackle this puzzle with appropriate strategies or let the genie out of the bottle.

1. Introduction

Marine environmental pollution has been receiving continuous close review in recent years due to the vastness of the environmental and ecological impairment caused by it. The amount and types of pollutants received by the ocean are as continually growing. Conventional pollutants occur naturally in coastal and marine water and its prevalence can be controlled to some extent unlike the class of pollutants designated as contaminants of emerging concern. The threat is due in the most part to the complexity of the pollutant structure and less known fate and transport processes of such contaminants. The scientific community is spending a great deal of time and resources for the detection of its sources, monitoring, and remediation of the effects of the emerging contaminants. Plastics and microplastics in the marine environment come under these class of pollutants (Browne et al., 2007) which have already upgraded their class from the emerging contaminants to an emerged threat (Avio et al., 2017).

Typically, these ocean plastics are classified according to the particle diameter, ranging from nanoplastics < 0.33 mm, microplastics between 0.33 and 5 mm to macroplastics > 5 mm (Andrady, 2011; GESAMP, 2015). The nano and microplastics tend to have a large surface area to volume ratio that can easily sorb waterborne contaminants harmful to the aquatic life. Though invented a century ago (Baekeland, 1909), the large scale production and use of plastics only dates back to ~1950 (Geyer et al., 2017). The durability, the lightweight, the low cost of mass production, the low market cost and other numerous variants suiting endless applications exploring the possibilities of organic chemistry have resulted in plastics invading every realm of human life and subsequently the environment. The global production of plastic has increased from 322 million metric tons (Mt) year^{-1} in 2015 to 348 million Mt year^{-1} in 2017 (PlasticEurope, 2018), excluding Polyethylene Terephthalate (PET), Polyamide (PA), Polypropylene (PP) and polyacryls-fibers. The global production shows a substantial increase in recent years irrespective of the environmental and societal problems caused by plastics. For instance, plastic bags blocking waste water systems had been largely responsible for floods with great loss of life in the Philippines (Pahl et al., 2017).

Plastics continue to be detected even in some of the remotest corners of our planet such as in the sea ice cores from the Fram Strait and central Arctic (Peeken et al., 2018), in the surface waters south-west of Svalbard (Lusher et al., 2015), in sub-surface waters of the central

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Arctic basin and in deep-sea sediments (La Daana et al., 2018; Bergmann et al., 2017), in marine sediments near Rothera Research Station, Antarctica (Reed et al., 2018) and in the Antarctic marine system (Waller et al., 2017). Due to its wide distribution, plastics within sediments are proposed as a practical stratigraphic marker of Anthropocene strata considering a mid-20th century beginning for this postulated epoch (Zalasiewicz et al., 2016). The ocean has been a receiver of the incessant influx of plastic materials of various types followed by the mass production and usage. This has caused substantial deterioration in the fragile marine biogeochemical ecosystem. It is by far the most prevalent debris item contributing an estimated 60 to 80% of all marine debris (Inniss et al., 2016). Nearly 700 marine species are known to interact with marine debris in recent years (Hardesty et al., 2015) compared to around 267 species over two decades ago (Laist, 1997), which is ~3-fold increase.

There are relatively few studies addressing the interaction between physical processes and plastics in the ocean. Most of these studies deal with the transport processes of plastics and its accumulation (Zhang, 2017; Brach et al., 2018; Horton and Dixon, 2018; Laxague et al., 2018; Gutow et al., 2018). To the best of our knowledge, this is the first study depicting the potential of plastics affecting the physical processes in the ocean and, we hope that this communication will pave the way for further detailed investigations, exploring the potential contribution of plastic pollution to the changes in marine water column physics and to the changing climate beyond the pale.

2. Global plastic production and types

The production and use of plastics peaked after the 1950s. The data regarding the global plastic production from 1950 to 2017, published by the Plastics Europe Market Research Group is collated from PlasticsEurope reports (PlasticsEurope, 2006–2018). The data include plastic materials (thermoplastics and polyurethanes) and other plastics (thermosets, adhesives, coatings and sealants), excluding fibers such as PET, PA, PP and polyacryl.

The global annual production of plastics has increased substantially (Fig. 1) in recent decades, paving the way for more plastic litter in the marine environment. The single-use plastics accounts for around 50% (Xanthos and Walker, 2017) of total plastics production. The majority of plastic wastes will find its way to the oceans through land-based sources or from marine-based operations. Table 1 indicates the most common types of plastic found in the marine environment and its production percentage in the global plastic production. Considering the fact that the most of the plastic types having higher percentage of production are single-use plastics such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), PP, polystyrene (PS), PET (UNEP, 2018), it will be more when waste is generated also. The most commonly encountered plastic types in the marine environment (LDPE, HDPE, PP), which are on par with the global production percentages, have specific gravity less than sea water (0.92, 0.94, 0.82) (Table 1). It implies that these plastics will float on the sea surface (Fig. 2a), based on hydrodynamic conditions. Plastics in marine water can also be semi-buoyant (Fig. 2b and c) depending on the type of plastic and the prevailing physico-chemical properties of the surrounding waters. In addition to the semi-buoyant plastic materials, a jellyfish can also be seen in Fig. 2c. Plastics debris affects marine mammals worldwide (Panti et al., 2019) and sea turtles often ingest plastic bags due to its resemblance to the jellyfishes which are natural prey of these primarily visual predators in the ocean (Schuyler et al., 2014).

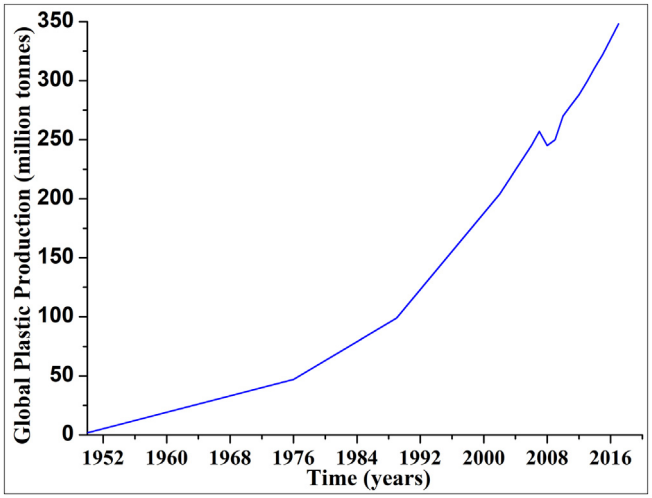

Fig. 1. Global annual production of plastics (1950–2017).

3. Marine plastics and physical processes: the reciprocality

Currently, most of the studies on marine plastics deal with issues such as plastics as a contaminant, methods of plastic identification, their sources, accumulation of organic and inorganic contaminants on the surface of plastics, leaching of chemicals from plastics to the water, harmful effects on organisms and food chain, effects on human health and transport-accumulation of the plastics. Most of these topics are not fully addressed yet and hence warrant further detailed investigation. The most incongruous nature of plastics in the marine environment is that we cannot formulate an adaptation strategy and the cost of mitigation efforts is very high. A plethora of studies are pouring in recent years, identifying triggers and consequences of plastics in the marine environment leading to better explanations and meliorations. For an overview, see the review articles (Cole et al., 2011; Wright et al., 2013; Hidalgo-Ruz et al., 2012; Van Cauwenberghe et al., 2015; Koelmans et al., 2016; Ziccardi et al., 2016; Auta et al., 2017; Andrady, 2017; Law, 2017; Rezania et al., 2018) which enumerate most of the published papers on this topic. As new results emerge, we observe that the marine environmental processes involving plastics and its implications can be catalogued as a compound event. This is a term now widely used in addressing climate extremes (Zscheischler et al., 2018) and by definition; it is an extreme impact that depends on multiple statistically dependent variables or events (Leonard et al., 2014).

Some studies (Welden and Lusher, 2017) have looked into the impacts of climate-related processes on microplastics in the ocean and contend that the plastic distribution may be greatly altered by global climate change. A recent study (Royer et al., 2018) has shown the evidence regarding the potential of plastics to be a key player in climate process and, the most commonly used plastics produce methane and ethylene due to the action of ambient solar radiation. These are greenhouse gases and the most produced and discarded synthetic polymer, polyethylene, is the major source of these gases. The conclusion of a decades-old report (Nigam, 1982) dealing with plastic pellets on the beach sand of Goa, India is as follows “Though they are not apparently causing any serious problem at present but their non-degradable nature and continuous accumulation may prove to be an environmental hazard in future”. Now after 36 years, plastic pollution is one of the foremost Gordian knots faced by humanity. Similarly, plastics can emerge as a future key component in the climate system, taking into consideration the pace of production and usage of unlimited variants of plastics. Plastics in the ocean often create public fear as well as environmental deterioration, similar to that of climate change.

Solar radiation can be inhibited as well as attenuated by optically active constituents (OACs) such as phytoplankton, suspended particles, dissolved organic matter (DOM) and colored detrital material (CDM) which are present in the upper water column (Bissett et al., 2001; Babin et al., 2003; Behrenfeld and Boss, 2006; Kim et al., 2015; Goncalves-Araujo et al., 2018). Common OACs of the ocean are colored dissolved organic material, phytoplankton, floating vegetation and suspended particulate material (Forget et al., 1999; Sathyendranath et al., 1989).

Table 1
Types of plastics encountered in the marine environment and its percentage with respect to the global production.

Plastic type	Acronym	Specific density compared to sea water (~1.02 g cm^{-3})	Global production (%)
Low-density polyethylene	LDPE	0.92	21%
High-density polyethylene	HDPE	0.94	17%
Polypropylene	PP	0.82	24%
Polystyrene	PS	1.09	6%
Nylon	PA	1.15	< 3%
Thermoplastic polyester	PET	1.37	7%
Poly(vinyl chloride)	PVC	1.3	19%
Cellulose acetate	CA	1.24	21%

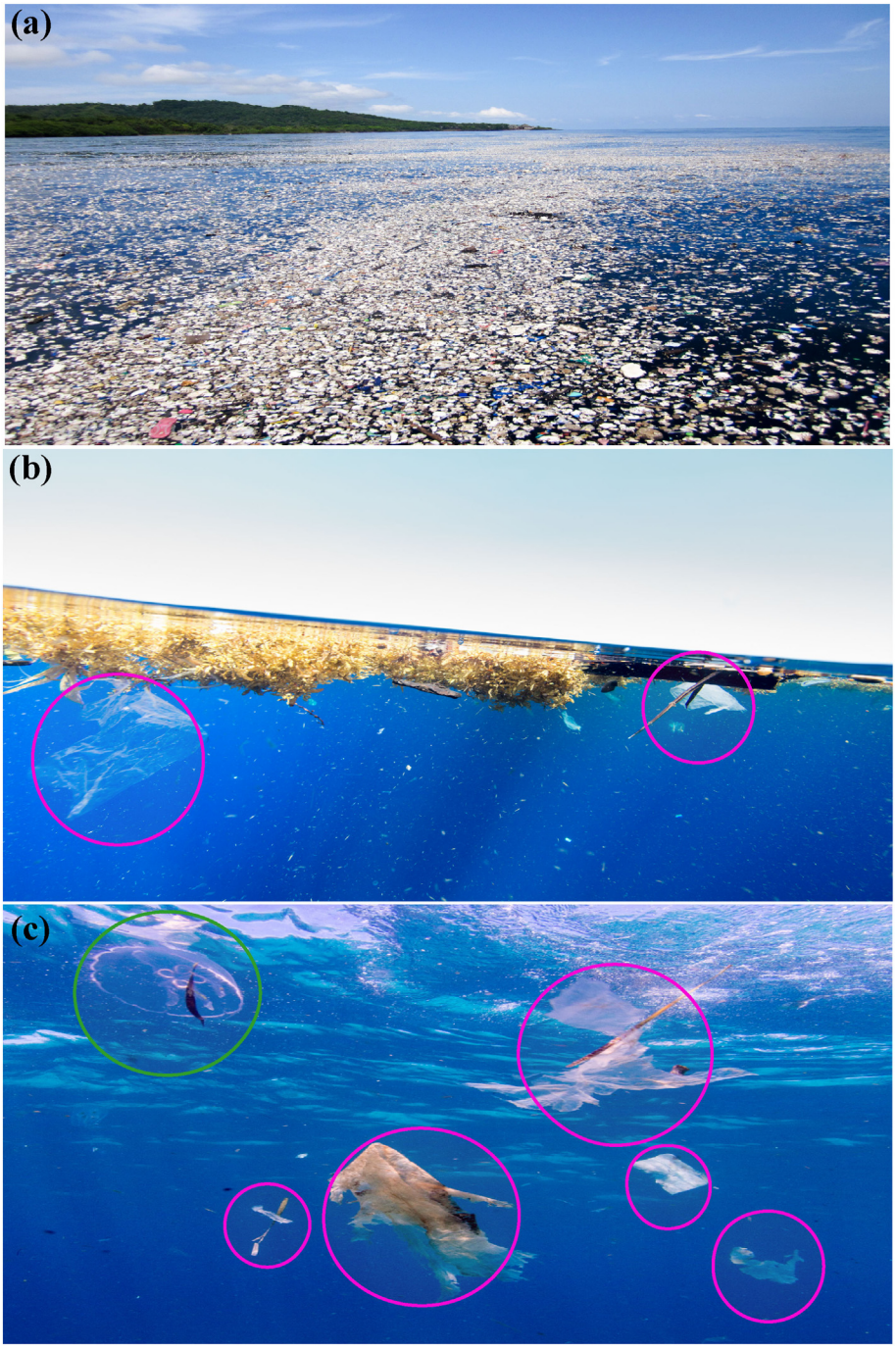

Fig. 2. a) Floating plastic debris in coastal waters (The Bay Islands, Honduras), b) Sea surface with floating Sargassum sea weed, semi-buoyant plastics (magenta circles) and small plastic fragments, c) semi-buoyant plastics and jellyfish (green circle). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

These OACs can limit the availability of solar radiation to the photic layer and can have further implications regarding the ocean heat storage. Phytoplankton, one of the most common OACs, is widely distributed in the ocean and encompasses a wide range of geographical distribution. It is a major contributor to the absorption and reflectance of radiation in the upper ocean and, is also one of the well investigated OACs in the marine environment. Phytoplankton cell sizes range widely over at least 9 orders of magnitude, from a cell volume ~0.1 μm^3 for the smallest cyanobacteria to > 10^8 μm^3 for the largest diatoms. The most frequently considered classes in the ocean (based on equivalent spherical diameter (ESD) of particles) are the picophytoplankton (ESD < 2 μm), the nanophytoplankton (ESD 2 – 20 μm), and the microphytoplankton (ESD > 20 μm) (Marañón, 2009). The abundance, wide geographical distribution range, optically active nature and, diversity in size and shape ranges make phytoplankton well comparable to the ocean plastics, at least in terms of physical aspects. There are several works addressing the optical properties of marine waters and phytoplankton from Jerlov (1976), Kirk (1984, 1994) to recent comprehensive reviews in ocean optics by Roy et al. (2011) and, Watson and Zielinski, 2013. The ocean surface layer which is rich in phytoplankton can trap more shortwave radiation than the surface layer without phytoplankton, which results in surface warming, subsurface cooling, ocean stratification and shoaling of the surface mixed layer. These changes in the physical state can have potential impact on the upper ocean circulation (Park and Kug, 2014).

More recently with the rise in ocean plastic pollution and disasters that result in floating marine debris, the spectral reflectance in different parts of the world ocean is no longer influenced by the typical OACs. Now, in addition to the common OACs, there are floating ocean plastics that contribute to ocean surface bright targets such as whitecaps, foam and breaking waves (Garaba and Dierssen, 2018). Currently, the amount of plastics and microplastics afloat in the surface layer may not have any substantial effect on the heat budget/physical processes. Recall how much more phytoplankton is out there in the ocean and if we are producing and dumping plastic at the current rate, it may attain near to similar amount/volume of the area currently occupied by phytoplankton. Another point to note is that there are seasonal waxing and waning of phytoplankton depending on the ocean biogeochemical conditions. This mechanism is absent in the case of plastics in sea water. Though biotic and abiotic degradation as well as deterioration of plastics occur in the marine environment through processes such as microbial biodegradation, hydrolysis, photodegradation, thermos oxidative degradation, dissolution, and mechanical degradation (Andrady, 1990, 2015; Shah et al., 2008; Cooper and Corcoran, 2010; Cooper, 2012), the stabilizers and other chemical additives in plastics enhances the resistance to these degradation mechanisms (Gewert et al., 2015). The end products resulting from the degradation can be micro and nano plastics (from large debris) and toxic chemicals (Barnes et al., 2009; Koelmans et al., 2015; Gewert, 2018) which can pose a ruinous effect on the marine environment. The exponential increase in the production and the use of plastics can result in the clustering of plastics in the thin sea surface micro-layer and the upper water column, which can be exacerbated by processes such as biofouling. If unchecked, the plastic concentration maybe even comparable to the distribution of phytoplankton (at least at major gyres and coastal waters). This increased concentration of plastics in the upper water column can lead to the alteration of the amount of radiation received by the ocean surface, which can induce far-reaching consequences in the prevailing physical and biogeochemical state of the ocean. Considering these facts, this research note proposes a hitherto unaddressed issue which can befall on the planet in the near future regarding the potential of plastics affecting the ocean physical processes.

4. Spectral characteristics of plastics and its effects on incoming solar radiation

Spectral reflectance $R(\lambda)$ of the ocean is the ratio between upwelling irradiance $E_u(\lambda)$ just below the sea surface and the total incoming or downwelling solar irradiance $E_d(\lambda)$ just above the sea surface at wavelength λ at the surface (depth Z = 0) and is expressed in Eq. (1):

$$R(\lambda, 0) = \frac{E_u(\lambda, 0)}{E_d(\lambda, 0)} \quad (1)$$

The essential climate and ocean variable R(λ) is a key proxy that is used to determine the apparent color of the ocean and estimate concentration of OACs of the ocean (Garaba and Zielinski, 2013; Morel, 1980). To showcase the spectral properties of plastics we present high quality hyperspectral measurements of 11 types of virgin plastic pellets common in marine plastic debris (Garaba and Dierssen, 2017). The pellets were from polyvinyl chloride (PVC), polyamide or nylon (PA 6.6 and PA 6), LDPE, PET, PP, PS, fluorinated ethylene propylene teflon (FEP), terpolymer lustran 752 (ABS), Merlon, polymethyl methacrylate (PMMA). The spectral reference library was generated using prior observations of various types of plastics that are being found in harvested plastics across most of the aquatic environments (Andrady, 2011; GESAMP, 2015; Hidalgo-Ruz et al., 2012). The data were generated by measuring spectral reflectance of dry marine-harvested macroplastics (regions on the west coastline of the USA) and microplastics (western North Atlantic waters). Details pertaining to the instruments used and sampling methodology are detailed in Garaba and Dierssen, 2018. We also adopt the concepts of the optical reflectance model proposed by Goddijn-Murphy et al., 2018 to assess the interaction of solar radiation with the plastics on the sea surface based on geometrical optics and the spectral signatures of both the plastic and seawater.

Furthermore, the floating plastics in the near-surface layer can interact with solar radiation reaching the ocean surface because plastics possess an optical signature in the radiation spectrum (Cloutis, 1989; Garaba et al., 2018; Garaba and Dierssen, 2018; Huth-Fehre et al., 1995). As more plastics are entering the marine environment, it is expected that they will become part of the typical natural OACs. Typical OACs interact with light mostly in the ultra-violet to near infrared spectrum whilst plastics interact with light from the ultra-violet to shortwave infrared spectrum. Spectral reflectance of the most common types of plastics and less common types of plastics encountered in the sea water is given in Figs. 3 and 4, respectively. The reflectance can be considered as a proxy for the light inhibition by a material and the figures indicate the potential of all the types of plastics in inhibiting wavelengths of solar radiation in the visible (VIS), near-ultraviolet

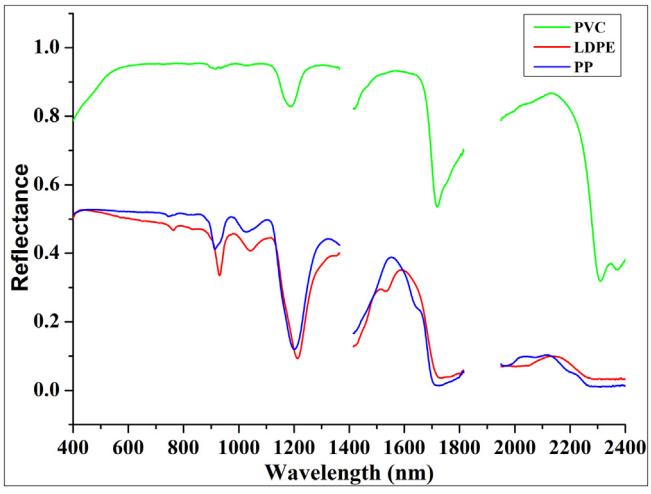

Fig. 3. Spectral reflectance of the most common types of plastics in seawater.

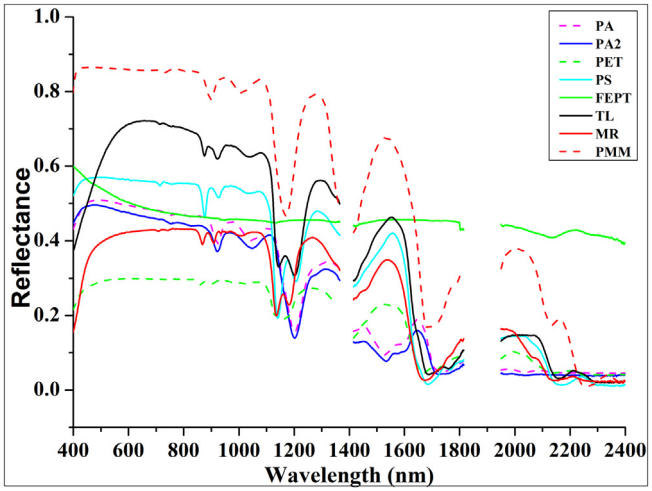

Fig. 4. Spectral reflectance of the other less common types of plastics in seawater.

(UV), and near-infrared (NIR) spectra, that is the shortwave radiation which plays an important role in oceanic processes. This modification of shortwave radiation penetration can interfere with the surface warming/cooling which in turn can influence the ocean stratification and mixed layer depth. Also, the plastics and microplastics may change the optical properties of the water column, thus affects physical processes in the near-surface/surface layer. The changes in the near-surface layer, in the long run, can eventually affect climate processes and can induce feedback cycles. The increased distribution of plastics in the ocean may contribute to the warming or cooling of the water column by attenuation, scattering or polarization of ambient light and thereby can also influence the ocean heat uptake.

Goddijn-Murphy et al., 2018 recently proposed an optical reflectance model based hyperspectral remote sensing algorithm for detecting floating plastics on the sea surface. The model for the sea surface littered with plastics considers the following ranges of wavelength: VIS (400–700 nm), NIR (700–1000 nm) SWIR (1000–2500 nm). Interaction of ambient light and the typical OACs will be affected by presence of the plastics per unit area observed by an optical sensor, this means the total bulk water leaving signal reaching a sensor can best be estimated by Eq. (2)

$$L_t(\lambda) = (1 - f)L_W(\lambda) + fL_p(\lambda) \quad (2)$$

$$f = \frac{A_p}{A_t} \quad (3)$$

where f, is the fraction of the target pixel covered by plastics, A_p is the area covered by the plastic in the target pixel (m^2), At is the total target area covered by a pixel of the optical sensor (m^2), L_w is the total water leaving radiance in the air (W/m^{-2} sr^{-1}), and L_p is the total plastic leaving radiance in the air (W/m^{-2} sr^{-1}).

In the case of semi-transparent and transparent plastics (Eq. (4)), subsurface upwelling light transmitted through the plastic also contributes to total water leaving radiance in the air.

$$L_p = \rho_p L_d + \tau_p L_{ws} \quad (4)$$

where ρ_p, is the radiance reflectance, τ_p is the transmittance, L_d is the downwelling radiance in air ($wm^{-2}sr^{-1}$), and L_{ws} is the subsurface upwelling radiance in water ($wm^{-2}sr^{-1}$).

Analogous to Eqs. (2) and (4), the downwelling radiance in water ($L_{ds}(\lambda)$) and total plastic leaving downwelling radiance in water (L_{ps}) are given by Eqs. (5) and (6), respectively.

$$L_{ds}(\lambda) = (1 - f)L_{ds,0}(\lambda) + fL_{ps}(\lambda) \quad (5)$$

$$L_{ps} = \tau_{pw}L_d + \rho_{pw}L_{ws} \quad (6)$$

where $L_{ds,0}$ is the sub-surface downwelling light without plastic, τ_{pw} is the fraction of downwelling radiance in air transmitted through plastic, and ρ_{pw} is the fraction of subsurface upwelling radiance in water reflected by plastic.

The 'shading' factor $\varepsilon(f,\lambda)$, which depends on the total surface area covered by plastics and the total reflectance from the sea surface having plastics $Rt(\lambda)$ is given by Eqs. (7) and (8), respectively.

$$\varepsilon(f,\lambda) = \frac{1 - f(1 - \tau_{pw}(\lambda)/\tau_w(\lambda))}{1 - f\rho_{pw}r_{ws}} \quad (7)$$

where τ_w and r_{ws} are the ratio between the sub-surface downwelling light without plastic and the downwelling radiance in the air, and the ratio between the subsurface upwelling radiance in water and the downwelling radiance in water respectively.

$$R_t(\lambda) = \varepsilon(f,\lambda)R_{w,0}(\lambda) + f(\rho_p(\lambda) - \varepsilon(f,\lambda)R_{w,0}(\lambda)) \quad (8)$$

The above Eqs. (2) to (8) (Goddijn-Murphy et al., 2018) represent the concept of reflectance by plastics, which confirms the attenuation and alteration of the available radiation in the photic zone. Large areas such as subtropical gyres where there is more plastic density, the photic depth may be reduced due to this effect. The depths at which different colors of light penetrate in coastal and open ocean waters are shown in the schematic diagram (Fig. 5). Water strongly absorbs light in the NIR to SWIR which could change when the sea surface and the surface water column are littered by plastics, ultimately affecting ambient radiation physics prevailing in the water column. Plastics are bright targets that are reflective in the VIS to SWIR spectrum as shown (Figs. 2 and 3) with a wide variability present in the natural environment, its potential effect on the ocean physical processes remains largely unknown. Furthermore, the reduction in the amount of radiation reaching the upper water column can affect the amount of heat storage. Since the stored heat in the ocean plays a major role in the climate of the planet, any changes in the heat budget can result in far-reaching consequences. Some of the near-surface layer processes which can be affected when there is excess plastic material in the water column are as follows: It can affect the normal gas exchange in the air-water interface leading to reduced dissolved oxygen, changes in effect of wind stress on the sea surface, affect the normal light and heat penetration into the ocean, photosynthesis and evaporation will be affected, changes can occur in the thermocline depth and fluctuations can happen in boundary layer physics. These cascading processes and their feedbacks have to be assessed further with in-situ experiments, field data and model simulations.

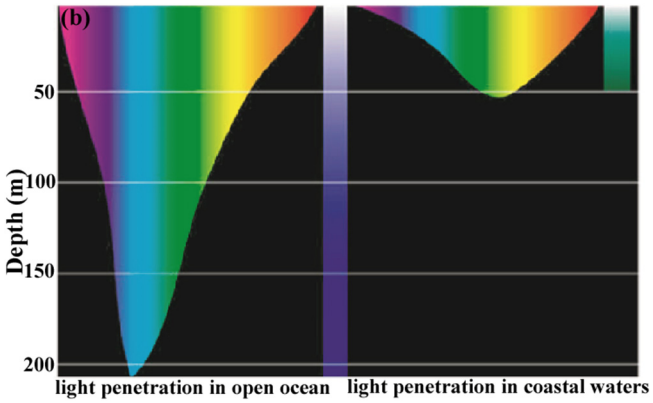

Fig. 5. Schematic diagram showing the depth at which different colors of light penetrate ocean waters (Image courtesy: Kyle Carothers, NOAA-OE).

5. Concluding remarks

The current spatial distributions of various types of plastics are increasing exponentially around the globe. Plastics are not immediately perishable unlike other kinds of organic waste generated by anthropogenic activities and being an artificial produce, the assimilative capacity of plastics in the ocean is almost nil. If we are loading the oceans with plastic at the current rate, the thin sea surface microlayer can have a substantial amount of plastic materials, especially at major gyres and coastal water which can affect other oceanic physical processes as proposed in this note. In that case, by the years 2050 and 2100, the plastic problem may be very severe, as depicted in a recent study (Geyer et al., 2017). Unlike the century old public conscience that the world's oceans have infinite capabilities to assimilate all types of waste generated on land, Oceans inclusive of ocean surface/upper water column is a finite space. A recent report shows that there will be more plastics than fish by 2050 (Ellen mcArthur Foundation Report, 2016), which shall pave the way for the plastics in the water column to interact with oceanic processes as proposed in the study. The changes in ocean physical processes can induce climate feedback cycles in the future. This is the time to tackle this puzzle with appropriate strategies before plastics evolve as one of the key players affecting the ocean physical processes. Also, the plastic problem in the oceans raises an inevitable ethical question regarding the interaction of humans in pestering other species and ecosystem in general. Epistemological and empirical biases are common in ocean plastic related studies due to the sudden surge in the number of studies in recent years. Interdisciplinary scientific programs using long term data and modelling studies can pave the way for a better understanding and can ensure a sustainable future as well as healthy oceans. International trans-boundary cooperation in terms of policies related to the plastic production, consumption and waste disposal, taking the prevailing socio-economic conditions into consideration, on a par with coherent scientific studies can create an unequivocal fortune in tackling ocean plastic pollution and associated problems. We conclude by quoting Villarrubia-Gómez et al., 2018, “irrespective of the recognition of plastic as a novel entity in the planetary boundaries framework, it is certain that marine plastic pollution is closely intertwined with global processes to a point that deserves careful management and prevention”.

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